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Heat-Resistant Cylindrical Diffuser for Interstitial Laser Coagulation: Comparison With the Bare-Tip Fiber in a Porcine Liver Model

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Background and Objective: **Interstitial laser coagulation is an experimental treatment to eliminate solid tumors such as hepatic metastases. The pattern of light emission from the fiber tip is probably an important factor in determining the size and shape of a lesion. A heat-resistant cylindrical light diffusing tip of 2 cm length was developed for this application. We performed an in vitro study to compare this diffusing-tip with a bare-tip fiber.**
Study Design/Materials and Methods: **Fiber ends were positioned between two porcine liver slabs (37°C) and Nd:YAG laser light (1064 nm) was guided through either fiber with an output of 3–9 W and exposure times of 6–18 minutes.**
Results: **Lesions produced by the cylindrical diffuser tip were significantly larger and more predictable. With the diffuser tip, lesions up to 36/23 mm (length/width) could be produced at 7 W and 9 min without any central charring. The maximum size of lesions produced with the bare-tip fiber was 32/20 mm at 6 W for 9 min with massive charring.**
Conclusions: **The results indicate that at optimal laser settings, the diffuser tip produces a larger coagulation volume than a bare-tip fiber. For clinical application, cylindrical diffusing fibers should be used with a diffusing length adapted to the diameter of the tumor. Lasers Surg. Medicine 20:304–309, 1997.**

Key words: liver; metastases; optical fibers; photocoagulation; thermotherapy

INTRODUCTION

Interstitial laser coagulation is a new method of producing localized tissue destruction that may be used to eliminate solid tumors, such as liver metastases, pancreatic carcinomas, brain glioma, and benign prostate hyperplasia [1]. The laser light is delivered to the tumor by one or more optical fibers that are inserted directly into the tissue. The type of fiber tip creating the largest lesion size is still a matter of discussion [2,3]. In the majority of cases, a so-called bare-tip fiber is used. With this fiber, the emission of light and hence the generated heat is concentrated around the tip (point light source), causing high temperatures that result in carbonization. The blackish material surrounding the tip absorbs the laser light strongly and suppresses its transmission into the tissue. Thus a charred fiber acts as a point *heat* source, and the size of the induced coagulation depends entirely on heat diffusion from

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the tip toward the tissue. A cylindrical diffusing fiber tip produces a homogeneous light emission over its light-diffusing length (distributed light source). By that, the emitted laser light is equally distributed into the tissue, and the induced coagulation depends on light transmission followed by heat production upon absorption in the tissue.

Previous experimental comparisons between both fiber tips showed that at a lower laser output and time, the point light source produced a larger lesion (with charring) than the distributed light source (without charring) [4–6]. However, the temperature gradient from fiber tip into the tissue is much less steep for a distributed light source than for a point light source [7]. Furthermore, it requires a higher laser output power for the distributed light source than for the point light source to reach the coagulation temperature [7].

We hypothesize that a distributed light source can potentially heat a larger area from the fiber tip and accordingly reach a larger coagulation volume than a bare-tip fiber. Monte-Carlo simulations, using the optical and thermal properties of native and coagulated tissue, support this hypothesis [7,8]. However, there are no supporting experimental data, as the fiber tips have not been tested at their individual optimal laser settings [5,6]. Furthermore, until recently, the available cylindrical diffusing fiber tips were too large in diameter and temperature unstable. We developed a diffusing tip with the same diameter as the standard 600 μm optical fiber that withstands temperatures of ~300°C. For a standardized comparison of both fiber tips, we designed an experiment using porcine livers in which the bare-tip and cylindrical diffuser were studied at various combinations of laser output and exposure time. In this way the biological effects of both fibers could be assessed at the optimal individual laser settings.

MATERIALS AND METHODS

Optical Fibers and Construction of Cylindrical Diffuser

Laserlight was transmitted through glass fibers (core diameter 600 μm, outer diameter 1.65 mm) with either a diffusing end of 21 mm, or a bare-tip fiber with a freshly cleaved end and the most distal coating stripped for 15 mm. Polishing of the freshly cleaved bare-tip fibers did not enhance reproducibility of lesion size and shape. The cylindrical diffuser used for these experiments (Lightstic™, Rare Earth Medical, of West Yarmouth, MA) was designed to withstand temperatures of 300°C. The diffusion region of the fiberoptic catheter consisted of epoxy containing scatterers, encased in fluoropolymer sheath. An end mirror was sharpened to ease insertion and was coated to reflect all of the 1064 nm light, enhancing uniformity and preventing light from propagating out of the end of the tip (Fig. 1). In Figure 2, an actual density profile of one of the tips is shown, transmitting >85%, with uniformities of typically ±7% along the diffusion region. Hot spots, which could overexpose areas of tissue, were never found. The tips were tested at 60 W CW in water for 60 seconds before use in the experiments.

Fig. 1. Schematic drawing of the cylindrical diffusing fibertip.

Laser Application

A Nd:YAG laser (MBB 4060 N) with a wavelength of 1064 nm was used. Illumination was performed with a laser output ranging from 3–9 W and exposure times of 6–18 minutes (Table 1). As in pilot experiments, the cylindrical diffusing tip carbonized at 6 W and 12 min (4,320 J), we decided not to test the combination of settings marked with cnt in Table 1. Each combination of settings was repeated three times.

Liver Tissue

Porcine livers were preserved at –20°C and gradually defrosted before each experiment. The different lobes were cleaved into two slabs of 2.5 cm thick [8,9]. Prior to illumination the liver slabs were gradually warmed between two warm water mattresses until a core temperature of 37°C was reached. Liver core temperature was recorded with a Ni(Cr)-NiK thermocouple (Thermodig N800, AIS, France).

Procedures

A fiber was placed between two liver slabs at a distance of at least 3 cm from a previously produced lesion. To keep the core temperature of the liver at 37°C during laser application, the top slab was covered with a warm water mattress. To ensure good contact between the two slabs, a weight of 1 kg was placed on top. After illumination the

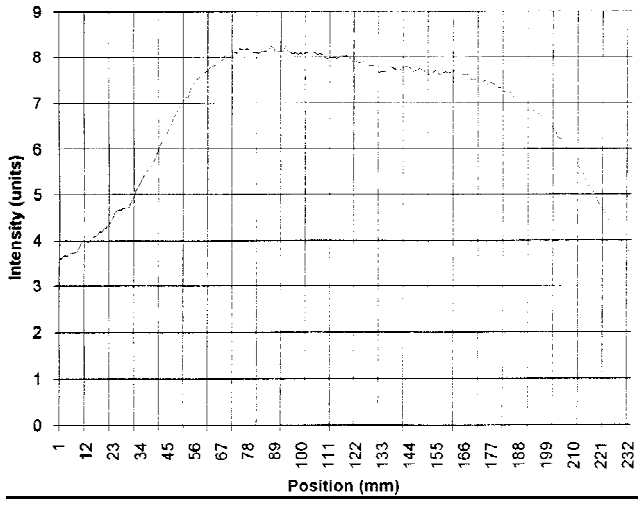

Fig. 2. Actual intensity profile of one of the diffusing-fiber tips used in the experiment, transmitting above 85% and having measured uniformities of typically ±7% along the diffusion region.

top slab was removed and length (parallel to the fiber) and width (perpendicular to the fiber) of the coagulated lesion were measured with calipers. The extent of the lesion was estimated as the macroscopically detectable (whitish) color change compared to normal colored liver parenchyma. Each lesion was checked for carbonization.

Tissue Temperature

Temperature distribution during illumination was measured at the combination of 6 W for 6 minutes (2,160 Joules). Fiberoptic thermosensors with a diameter of 0.5 mm were coupled to a Luxtron thermometry unit (Luxtron Corp., Santa Clara, CA) and inserted parallel to the laser fiber into the tissue at axial distances of 3, 8, and 13 mm from the fiber tip. Temperature was sampled every second and stored using a computer. Self adsorption was tested in air and determined as an immediate temperature rise of 3°–4°C at 1 cm distance. Influence on the temperature measurements because of self-adsorption was not taken into consideration in the porcine liver experiments, as this immediate temperature rise could not be demonstrated.

Statistics

The values are expressed as mean ± standard error of the mean (SEM). For each fiber type, a multiple linear regression model for length and width was fitted, including power and energy as explanatory variables. Possible deviations from linearity for the explanatory variables were tested, which resulted in adding a quadratic term for power in the regression equation for width for the diffuser-tip fiber, but not for the bare-tip fiber. Deviation from parallelism of the regression lines for length of each fiber type was tested using a t-test on the regression coefficient. To test for variability in lesion size of the repeated measurements between the two fibers, a F-test, i.e. variance ratio test, was performed with the residual mean of squares. Values were considered statistically significant at P values <0.05.

RESULTS

Macroscopy

Typical bare-tip fiber lesions were irregular in shape with central charring and sometimes charring parallel along the fiber (Fig. 3a). The cylindrical diffuser-tip lesions were characteristically ellipse in shape (Fig. 3b). With this tip slight charring was found when 9 W for 6 in was applied (3,240 J); however, no destruction of the fiber tip occurred. Damage because of massive charring occurred when 5 W were applied for 18 in (5,400 J), marked with [a] in Table 1.

Lesion Size

The relationship between length and width of the lesion for energy applied is given in Figure 4 (bare-tip fiber) and Figure 5 (diffusing-tip fiber). The lines of various power output have a similar slope for increasing energy applied. For both types of fibers, length and width also enlarged with increasing power. This incline in lesion size was significantly larger for the cylindrical diffuser, as computed with the multiple linear regression model (length $P = 0.048$, width $P = 0.042$).

Tissue Temperature

Table 2 shows the temperature distribution measured at a distance of 3, 8, and 13 mm from the fiber tip. Close to the fiber, tissue temperature was markedly higher for the bare-tip fiber, 260 ± 17°C vs. 123 ± 5°C for the diffusing-tip. At 8 mm, the tissue temperature was comparable for both fibers. At the distance of 13 mm, the mean temperature for the diffusing-tip fiber was close to the coagulation temperature (58 ± 3°C), whereas for the bare-tip fiber values were more in the range of the starting core temperature (39 ± 1°C). The standard errors of the mean (SEM) of the mean

TABLE 1. Laser Energy (J) Applied for Each Combination of Power and Exposure Time

	Exposure time (min)				
Power (W)	6	9	12	15	18
3	1,080	1,620	2,160	2,700	3,240
4	1,440	2,160	2,880	3,600	4,320
5	1,800	2,700	3,600	4,500	5,400[a]
6	2,160	3,240	4,320[b]	cnt	cnt
7	2,520	3,780	cnt	cnt	cnt
8	2,880	4,320	cnt	cnt	cnt
9	3,240	cnt	cnt	cnt	cnt

[a]Damage to the diffuser tip, not tested.
[b]Damage to the diffuser tip, tested only for the bare-tip fiber.
cnt = combinations not tested.

temperature values were significantly higher for the bare-tip fiber ($P = 0.015$).

Factors Influencing Lesion Size

The lesion size was more reproducible for the diffusing-tip fiber compared to the bare-tip fiber. The variance ratio test was significantly different from F = 1, both for length (F = 2.01, $P = 0.032$) and width (F = 2.48, $P = 0.039$). For the diffusing tip, the laser output was a more important factor determining lesion size than exposure time, comparing regression coefficients computed with the multiple linear regression model ($b_{power} = 2.078$; $b_{time} = 0.0032$).

DISCUSSION

Bare-tip fibers, which are easy to make and inexpensive to produce, are often used in interstitial laser coagulation. Moreover, it has been suggested that a point light source produces a larger volume of coagulation necrosis than a distributed light source at the same laser output and exposure time [2,4,5]. Our in vitro experiments show that the lesion size at lower laser outputs was larger for the bare-tip fiber than for the cylindrical diffusing-tip fiber. However, at higher laser output the size for the diffuser increased, whereas the size of the lesion for the bare-tip fiber seemed to reach a plateau.

Although we used healthy, previously preserved porcine liver, it is most likely that the similar difference between the bare-tip fiber and the diffusing-tip fiber will occur in vivo. However, the thermal and optical properties of tumor tissue may influence the different mechanisms of heating tissue (thermal diffusion versus light transmission and subsequent heat production) in a different way [10]. It can be hypothesized that the difference in lesion size between the two fibers may be larger in vivo. When using a bare-tip fiber, its mechanism of carbonization and subsequent thermal diffusion may be more influenced by the cooling produced by blood flow than the heating mechanism of the diffusing-tip [11].

One of our goals was to determine the maximal lesion size for both fibers at their optimal individual combination of power and exposure duration. From Figure 5 it can be noted that the size of the lesion for the bare-tip fiber has reached a plateau at 6 W for 9 min. Once charring around the bare-tip fiber has occurred and light penetration into the tissue is limited, further absorption of laser energy is less effective [12,13]. Ultimately at higher laser and power settings, lesion size for a cylindrical diffuser also will be limited by the maximal laser light penetration and heat diffusion into the tissue.

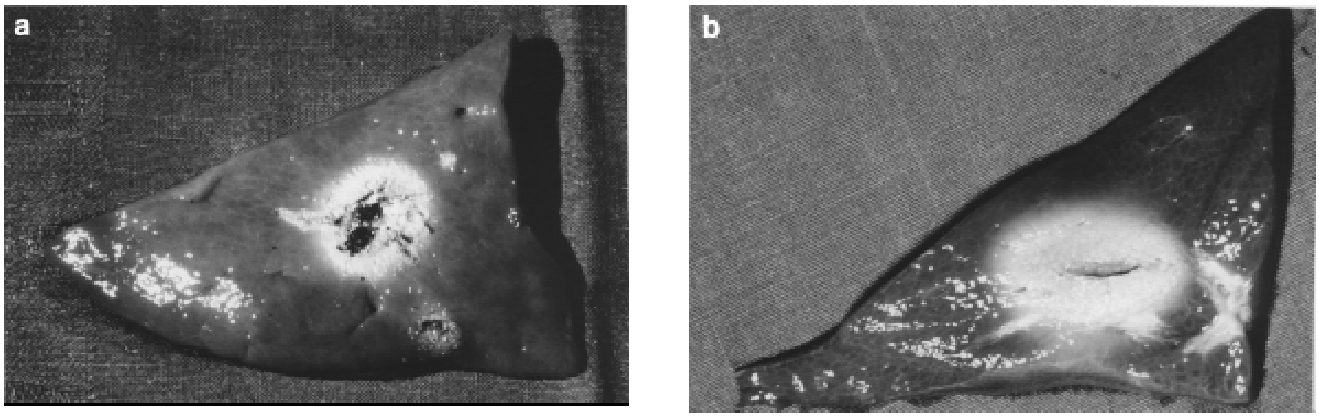

Fig. 3. A macroscopic view of a typical lesion (6 W for 6 min, 2,160 J) created with (**a**) the bare-tip fiber (24×18 mm) and (**b**) with the cylindrical diffusing-tip fiber (34×24 mm).

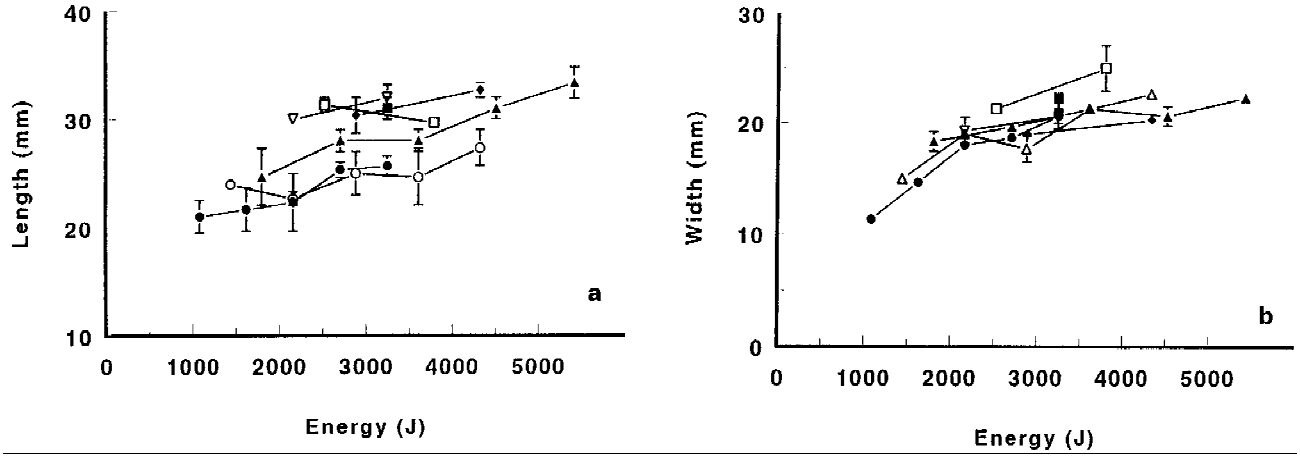

Fig. 4. Length (**a**) and width (**b**) of the coagulated lesion versus energy applied for the bare-tip fibre. Each line represents a fixed laser power setting as indicated (-●- 3 W, -○- 4 W,-▲- 5 W,-▽- 6 W, -□- 7 W, -◆- 8 W, -■- 9 W). Each point represents the mean ± SEM of three experimental results.

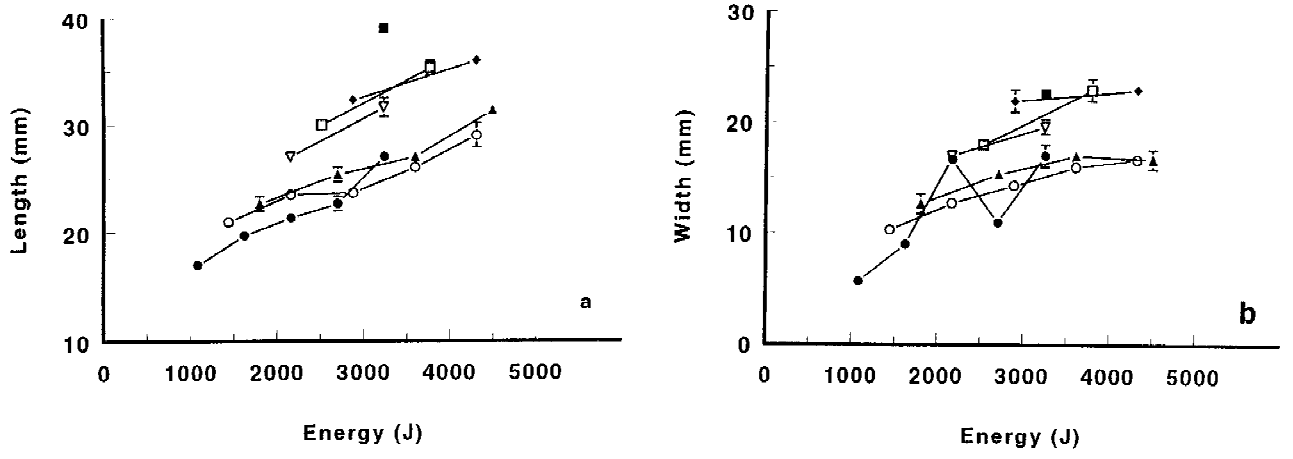

Fig. 5. Length (**a**) and width (**b**) of the coagulated lesion versus energy applied for the cylindrical diffusing-tip fibre. Each line represents a fixed laser power setting as indicated (-●- 3 W, -○- 4 W, -▲- 5 W, -▽- 6 W, -□- 7 W, -◆- 8 W, -■- 9 W). Each point represents the mean ± SEM of three experimental results.

The temperature profiles as determined from measurements at three distances from the fiber tip do confirm investigations of Wyman [9] and calculations of Roggan et al. [7]. They predicted a higher tissue temperature close to the light fiber for the bare-tip fiber with a steeper temperature gradient toward the tissue periphery compared to the cylindrical diffusing tip. Although the location of the thermofibers was critical, we take the view that the six repeated measurements give a good indication of the actual temperature profile.

Especially for the cylindrical diffuser, power was a more important factor in determining lesion size than exposure time. Although the amount of energy delivered at the combination 5 W and 15 in (4,500 J) is higher than for the combination 8 W and 9 in (4,320 J), the lesion size created by the latter was considerably larger. Therefore, in a clinical application, increasing power will be more efficient than prolonging exposure times in destroying larger tumors.

The unpredictability for bare-tip fiber-created lesions could be explained by the variability in the time at which charring occurs, which determines the mechanism of heating. This could also account for the larger variation in tissue temperature distribution for the bare-tip fiber measured during illumination. Similar results were

TABLE 2. Mean Tissue Temperature ± SEM (°C) at Various Exposure Times at 3, 8, and 13 mm from the Fiber Tip

	Exposure time					
Distance (mm)	1 min	2 min	3 min	4 min	5 min	6 min
Bare-tip fiber						
3	95 ± 9	131 ± 11	220 ± 20	249 ± 19	260 ± 20	260 ± 17
8	62 ± 5	71 ± 4	84 ± 4	100 ± 7	110 ± 4	115 ± 8
13	36 ± 1	38 ± 1	38 ± 1	39 ± 1	39 ± 1	39 ± 1
Diffusing-tip fiber						
3	66 ± 3	91 ± 4	111 ± 4	123 ± 5	124 ± 4	123 ± 6
8	46 ± 2	50 ± 2	63 ± 2	74 ± 3	85 ± 3	101 ± 6
13	37 ± 1	39 ± 1	43 ± 2	48 ± 2	52 ± 3	58 ± 2

*Tissue illuminated with 6 W for 6 minutes (2,160 J), n = 6.

reported Harries et al. [2] in a clinical study on interstitial laser therapy using a bare-tip fiber, as their results were more predictable when using a precharred fiber.

Conclusions

In this study we found that lesions produced by a cylindrical diffuser were significantly larger and more reproducible than with a bare-tip fiber. These findings imply that interstitial laser coagulation should be performed with a cylindrical diffusing-tip fiber. Charring should be avoided: (1) to maintain the integrity of the diffusing fiber, (2) to maximize the size of the coagulation necrosis, and (3) to ensure reproducible results. An important additional advantage of a cylindrical diffuser is that its length can be adapted to the relevant tumor size. By that, tumors of 3–4 cm can be treated over their entire diameter in one session, whereas the bare fiber needs to be pulled back several times [14]. The diffuser tip may therefore also increase the preciseness of tumor destruction.

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